

Achromatic Fiber-Optic Power Splitter and Related Methods

Cross-reference to Related Applications

This application claims the benefits of and priority to U.S. provisional patent application serial no. 60/426,987 filed on November 15, 2002, the entire disclosures of which
5 are herein incorporated by reference.

Government Rights

The subject matter described herein was supported in part by The United States Navy, Contract No. N00030-01-C-0022. The U.S. Government has certain rights in this invention.

Field of the Invention

10 The invention relates generally to optical splitters, and more particularly to achromatic optical splitters.

Background of the Invention

Power splitters and couplers have important military and commercial telecommunications and optical applications. The most common power splitters based on
15 optical fiber are directional couplers. Fused-fiber directional couplers propagate two modes along multiple optical fibers. One of the two modes is an even spatial function. This mode is also the lowest order mode. The other mode is an odd spatial function. Although the light that enters the coupler may be single mode, two modes evolve as the light travels along the coupler, and the modes interfere in the coupling region. If the length or temperature of the
20 coupling region of the coupler changes, or the polarization or wavelength of the light traveling the coupler changes, interference between the modes will change. Consequently, the spectral shape of the light input into the fiber and/or the power split ratio (the ratio of

output intensity from a first channel to the output intensity of a second channel) will change as well, which inhibits the performance and reliability of the signal output from the coupler.

Polished fiber directional couplers utilize evanescent coupling between adjacent waveguides. In addition, three port Y-splitters are planar waveguides that use a single waveguide split into multiple paths. Planar Y-splitters suffer from power split ratios that are sensitive to the polarization state of the incoming light. Planar Y-splitters also do not preserve the spectral profile, nor the polarization state of the input light.

Summary of the Invention

The invention, in one aspect, relates to an achromatic power splitter formed from multiple optical fibers. The achromatic power splitter of the invention, preferably, operates single mode and does not form higher order modes. This permits the device to operate substantially insensitive to wavelength and to operate broadband. The achromatic power splitter, in one embodiment, is designed so that only one type of mode, i.e., the lowest-order even mode, is present in the input region. The power split ratio of the achromatic power splitter of the invention is insensitive to changes in the wavelength and polarization of the input light, as well as environmental changes, e.g., temperature. According to one feature, light from the output fibers has substantially the same polarization state and substantially the same spectral profile as the input light. According to another one feature, the power split ratio is substantially unchanged if the splitter is exposed to ionizing radiation, e.g., gamma-rays or X-rays.

In one aspect, the invention provides a method of forming an optical device. The method includes fusing portions of a plurality of optical fibers to form a fused fiber region, and cleaving the fused fiber region, thereby forming a fused end. A spliced fiber is formed

by splicing an end of an independent optical fiber to the fused end such that the independent optical fiber is in optical communication with the first and second optical fibers. Reducing a cross-section of the spliced fiber forms an optical device propagating light with the lowest-order even mode. At least one of the optical fibers may be single-mode fiber. In one
5 embodiment, the reducing step includes heating and pulling the spliced fiber. The method may include reducing the cross-section of the spliced fiber to less than about 50 μm .

In various embodiments, the method includes forming the optical device such that the ratio of output from at least two of the plurality of optical fibers is independent of wavelength of light input into the independent optical fiber, polarization of light input into the
10 independent optical fiber, temperature of the optical device, and/or exposure of the optical device to ionizing radiation. The method may include forming the optical device such that the spectral profile of light output from at least one of the plurality of optical fibers and is substantially the same as the spectral profile of light input into the independent optical fiber. In one embodiment, a portion of the optical device is disposed in a casing.

15 In another aspect, the invention provides another method of forming an optical device. The method includes forming a hybrid fiber by splicing a coreless optical fiber to a first optical fiber, and fusing a portion of a second optical fiber to a portion of the hybrid fiber to form a fused fiber region. Reducing a cross-section of the fused fiber region forms an optical device propagating light with the lowest-order even mode. In one embodiment, at
20 least one of the first and second optical fibers is a single-mode fiber. In one embodiment, the reducing step includes heating and pulling the fused fiber region.

In various embodiments, the method includes forming the optical device such that the ratio of output from the first optical fiber to output of a first end of the second optical fiber is

independent of wavelength of light input into a second end of the second optical fiber, polarization of light input into a second end of the second optical fiber, temperature of the optical device, and/or exposure of the optical device to ionizing radiation. The method may include forming the optical device such that the spectral profile of light output from the first
5 optical fiber and a first end of the second optical fiber is substantially the same as the spectral profile of light input into a second end of the second optical fiber. In one embodiment, the fused fiber region includes the second optical fiber and at least two hybrid fibers prior to the reducing the fused fiber region.

In yet another aspect, the invention provides an optical device including an input
10 region, a fused fiber region in optical communication with the input region, and an output region in optical communication with the fused fiber region. The input region includes a portion of a first optical fiber and a portion of a coreless optical fiber, while a portion of the fused fiber region has a diameter less than that of the input region. The output region includes a portion of the first optical fiber and a second optical fiber. The input region, the
15 fused fiber region, and the output region all propagate the lowest-order even mode. In one embodiment, the input region includes a first optical fiber and portions of at least two coreless optical fibers, and the output region includes one more optical fiber than the number of coreless optical fibers.

In still another aspect, the invention provides an apparatus including a first optical
20 fiber spliced to a fused end of at least two optical fibers. The first optical fiber and the fused end form a spliced fiber region, and the optical fibers only propagate light with the lowest-order even mode.

Other aspects and advantages of the invention will become apparent from the following drawings, detailed description, and claims, all of which illustrate the principles of the invention, by way of example only.

Brief Description of the Drawings

5 The advantages of the invention described above, together with further advantages, may be better understood by referring to the following description taken in conjunction with the accompanying drawings. In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

10 Figure 1 depicts an illustrative embodiment of an achromatic power splitter.

 Figure 2 depicts exemplary cross-sectional views of the formation of the achromatic power splitter shown in Figure 1.

 Figure 3 shows additional cross-sectional views of the formation of the achromatic power splitter shown in Figure 1.

15 Figure 4 depicts another exemplary embodiment of an achromatic power splitter.

 Figure 5A depicts two optical fibers prior to being fused together.

 Figure 5B shows a fused fiber.

 Figure 6 shows an illustrative embodiment of a fused fiber cleaved into two sections.

 Figures 7A shows an exemplary embodiment of an optical fiber and a cleaved fiber
20 section prior to being spliced together.

 Figure 7B shows an illustrative embodiment of a spliced fiber.

 Figure 8 shows an exemplary embodiment of an achromatic power splitter disposed within a protective casing.

Detailed Description of the Invention

For the purposes of this application, the achromatic power splitter is achromatic in at least two respects: the output power split ratio of the splitter is independent of the input wavelength and the spectral profile of the light that exits the splitter is substantially the same as that of the input light. Furthermore, as used herein, the term “splitter” refers to splitters, couplers, taps and switches. In addition, as used herein, “light” refers to the optical part of the electromagnetic spectrum between about 200 nm and about 40,000 nm.

Figure 1 depicts an illustrative embodiment of an achromatic power splitter 100 that includes a coreless optical fiber 104 having cladding 106, a first optical fiber 108 having a first end 112 and a second end 116, and a second optical fiber 120. The first and second optical fibers 108, 120 include core regions 124, 126, respectively, and cladding regions 128, 130, respectively. The coreless optical fiber 104 and the first end 112 of the first optical fiber 108 form an input region 132 for the achromatic power splitter 100, and the second end 116 of the first optical fiber 108 and the second optical fiber 120 form an output region 136. The region where the three fibers 104, 108, 120 are coalesced together forms a fused fiber region 140, which itself includes a first tapered region 144, a central region 148, and a second tapered region 152.

The achromatic power splitter 100 operates in a single mode state because the input region 132 operates in a single-mode state. As described above, single-mode operation enhances the wavelength insensitivity of the achromatic power splitter 100. Preferably, the first and second optical fibers 108, 120 are single-mode fibers, e.g., SMF-28[®] fibers available from Corning, Inc., although in various embodiments multi-mode fibers may be used. The coreless optical fiber 104 may be a pure silica fiber, e.g., available from Lucent

Technologies. In various embodiments, one or more of the optical fibers **104, 108, 120** includes a coating disposed on the cladding region. The coating may be removed prior to formation of the achromatic power splitter **100**.

In operation, power P_0 in the form of light is input into the input region **132**. The
5 light propagates through the core **124** of the first optical fiber **108**. As the light propagates through the first tapered region **144**, the core **124** reduces in diameter, and the light begins to penetrate further into the cladding regions **106, 128** of the coreless fiber **104** and the first optical fiber **108**, respectively. For example, for a SMF-28[®] fiber having a diameter of about 125 μm and a core diameter of about 8.2 μm and carrying light with a wavelength of about
10 1550 nm, about 80% of the light is confined within the core. As the SMF-28[®] fiber is drawn down to smaller diameters, less light is confined to the core.

In the central region **148**, the diameter of the core **124** is reduced such that the cladding regions **106, 128** primarily guide the light. As the light enters the second tapered region **152**, the diameters of the cores **124, 126** of the first and second optical fibers **108, 120**
15 increase and begin to guide the light once again. Using techniques described in more detail below, the relative splitting of light between the two optical fibers **108, 120** may be controlled. This splitting is reflected in the power split ratio of powers P_1, P_2 exiting their respective optical fibers **108, 120** in the output region **136**.

The coreless optical fiber **104** does not transmit light into or out of the achromatic
20 power splitter **100**. Indeed, a power splitter may be formed without a coreless optical fiber, but it then becomes more difficult to process the splitter. The coreless optical fiber **104** provides additional material to the fused region **140** during formation of the tapers and permits a nearly symmetric profile of the achromatic power splitter **100**. Without the

coreless optical fiber, the integrity of the fused region becomes more difficult to maintain because there is less material on the input side of the splitter than the output side.

In addition, after forming the achromatic power splitter **100**, the cladding regions **106**, **128** of the coreless optical fiber **104** and the first optical fiber **108**, respectively, may be
5 shaved down in the first tapered region **144** so that the core **124** is located in the center of the fibers **104**, **108**, instead of off-center in the first tapered region **124**.

A splice machine and a workstation for making fused-fiber couplers may be used to form the power splitters. Figure 2 depicts exemplary cross-sectional views **156**, **160**, **164** of the achromatic power splitter **100** shown in Figure 1. The coreless optical fiber **104** is
10 spliced to the second optical fiber **120** to form a hybrid fiber **168**. View **156** is a section of the first optical fiber **108** and the hybrid fiber **168** in the fused fiber region **140**. Note that the core **126** shown in view **156** is that of the second optical fiber **120**, so this section represents a second optical fiber portion of the hybrid fiber **168**.

The first optical fiber **108** and the hybrid fiber **168** are fused so that the two fibers
15 coalesce to form a fused fiber **172** in the fused fiber region **140**. The progression of the fusing is shown in views **160** and **164**. In some embodiments, the average diameter of the fused fiber **172** is equal to or larger than the diameter of the first optical fiber **108** and/or the hybrid fiber **168**. For example, starting fibers with diameters of about 80 μm or about 125 μm may be used. In some embodiments, the fused fiber **172** in the fused fiber region **140** has
20 a substantially circular cross-section over a length of about 15 mm.

During fusing of the fibers, the fibers may be rotated (not twisted) while being fused. The rotations may be in about 180 degrees increments. Low speed pulls and long heating regions are preferred to minimize size reduction, and therefore retain a fused fiber **172** with a

diameter greater than or equal to that of the starting fibers. For example, for an about 125 μm fiber, a pulling rate of about 1.0 mm/min and a heating region of about 5 mm may be employed to pull the fibers a total of about 20 mm. Low flame temperatures also minimize size reduction. A typical flame temperature, e.g., for fusing silica, is about 1,500° C.

5 The diameter of the fused fiber 172 is then reduced to form the achromatic power splitter 100. Figure 3 shows a progression of cross-sectional views 164, 176, 178 of the fused fiber 172 during formation of the achromatic power splitter 100 shown in Figure 1. Reducing techniques known in the art, such as heating and/or pulling (not order specific) down the diameter of the fused fiber 172, are used. For a power splitter with starting fibers
10 with diameters of about 125 μm , the final dimension, shown in view 178, is about 50 μm . For a power splitter with starting fibers with diameters of about 80 μm , the final dimension, shown in view 178, is about 32 μm .

In addition, the output of the achromatic power splitter 100 may be monitored during formation of the splitter. This may include monitoring power versus time and/or measuring
15 excess losses during the fusing and pulling processes. By monitoring the output, the splitting characteristics may be optimized. Power splitters with virtually any splitting ratio may be formed, e.g., from 99:1 to 50:50, although a splitting ratio between about 60:40 and about 50:50 is preferred.

When reducing the diameter of the fibers, higher pull speeds and shorter heating
20 region, as compared to those parameters used when fusing the fibers, are used to increase size reduction in the central region 148, i.e. finish with a fused fiber 172 with a diameter about 2.5 times smaller than that of the starting fibers. In addition, a higher flame temperature may be used to concentrate size reduction in the central region 148.

In another embodiment, the achromatic power splitter **100** may be formed with an output region having three or more optical fibers. In such an embodiment, the corresponding input region includes a first optical fiber and two or more coreless optical fibers, e.g., the number of coreless optical fibers forming the input region equals one fewer than the number of optical fibers forming the output region. The techniques described above are used to form this embodiment of the achromatic power splitter.

Figure 4 shows an exemplary embodiment of an achromatic power splitter **200** that includes a first optical fiber **204** having a core **208** and a cladding region **212**, a second optical fiber **216** having a core **220** and a cladding region **224**, and a third optical fiber **228** having a core **232** and a cladding region **236**. The first optical fiber **204** (also referred to as an “independent” optical fiber) forms the input region **240**, while the second and third optical fibers **216**, **228** form the output region **244**. The region where the three fibers **204**, **216**, **228** are coalesced together forms a fused fiber region **248**, which itself includes a first tapered region **252**, a central region **256**, and a second tapered region **260**.

As described above with reference to the achromatic power splitter **100**, the achromatic power splitter **200** operates in a single mode state because the input region **240** operates in a single-mode state. As described above, single-mode operation enhances the wavelength insensitivity of the achromatic power splitter **200**. Preferably, all the optical fibers **204**, **216**, **228** are single-mode fibers, e.g., SMF-28[®] fibers, although in various embodiments multi-mode fibers may be used. In some embodiments, one or more of the optical fibers **204**, **216**, **228** include a coating disposed on the cladding region of the fiber. The coating may be removed prior to formation of the achromatic power splitter **200**.

In operation, power P_0 in the form of light is input into the input region 240. The light propagates through the core 208 of the first optical fiber 204. As the light propagates through the first tapered region 252, the core 208 reduces in diameter, and the light begins to penetrate further into the cladding region 212 of the first optical fiber 204. In the central
5 region 256, the diameters of the cores 208, 220, 232 of the respective fibers are reduced such that the cladding regions 212, 224, 236 guide the light. As the light enters the second tapered region 260, the diameters of the cores 220, 232 of the second and third optical fibers 216, 228, respectively, increase and begin to guide the light once again. As described above, the relative splitting of light between the second and third optical fibers 216, 228 may be
10 controlled. This splitting is reflected in the relative power or intensity of powers P_1 , P_2 exiting their respective optical fibers 108, 120 in the output region 244.

A splice machine, a cleaving machine, and a workstation for making fused-fiber couplers may be used to form the power splitters. To summarize the formation process, two optical fibers are fused together to form a substantially circular cross-section, and the fused
15 fiber is cleaved at or near the center. Another optical fiber is then spliced to one of the cleaved halves to form a spliced fiber. The diameter of the spliced fiber in the spliced region is then reduced to the working diameter.

Figure 5A depicts the second optical fiber 216 and the third optical fiber 228 prior to fusing. At least a portion of each fiber 216, 228 is fused together to form a fused fiber 264,
20 as shown in Figure 5B. The first and second optical fibers 216, 228 coalesce to form a substantially circular cross-section with a diameter approximately equal to the diameter of one of the starting fibers. For a starting fiber with a diameter of about 125 μm , the diameter of the central fused section is between about 100 μm and about 150 μm . The length of the

central fused section is about 15 mm. In a preferred embodiment, the substantially circular cross-section extends for a length of about 10 mm. The output of the fused fiber **264** may be monitored while the fibers are being fused, as described above.

During fusing of the fibers, the fibers may be rotated (not twisted) while being fused.

5 The rotations may be in about 180 degrees increments. As described above, low speed pulls, long heating regions, and low flame temperatures are preferred during fusing to minimize size reduction of the fused fiber **264**.

Figure 6 shows an illustrative embodiment of the fused fiber **264** cleaved into a first section **268** and a second section **272**, each section having a fused end **276**, **280** respectively.

10 The fused fiber **264** is cleaved at or about the center of the fused region. Preferably, each fused end **276**, **280** is examined, e.g., with a microscope, to determine the quality of the cleave. In another embodiment, the achromatic power splitter **200** is formed with an output region having three or more optical fibers, i.e., a fused end **276**, **280** of the fused fiber **264** includes three or more optical fibers.

15 A suitable section **268** or **272** of the fused fiber **264** that was cleaved is then spliced to the first optical fiber **204** shown in Figure 4 above. Figures 7A shows an exemplary embodiment of the first optical fiber **204** and the first section **268** prior to splicing the first optical fiber **204** to the fused end **276** of the first section **268**. Figure 7B shows an illustrative embodiment of a spliced fiber **284**.

20 The diameter of the spliced fiber **284** shown in Figure 7B is then reduced to form the achromatic power splitter **200** shown in Figure 4. Reducing may be done by heating and pulling (not order specific). For a power splitter with starting fibers with diameters of about 125 μm , the final dimension of the central region **256** shown in Figure 4 is about 50 μm . For

a power splitter with starting fibers with diameters of about 80 μm , the final dimension of the central region **256** is about 32 μm .

In addition, the output of the achromatic power splitter **200** may be monitored during formation of the splitter. This may include monitoring power versus time and/or measuring
5 excess losses during the fusing and pulling processes. As described above, by monitoring the output, the splitting characteristics may be optimized. Power splitters with virtually any splitting ratio may be formed, e.g., from 99:1 to 50:50, although a splitting ratio between about 60:40 and about 50:50 is preferred.

When reducing the diameter of the fibers, higher pull speeds and shorter heating
10 regions, as compared to those parameters used when fusing the fibers, are used to increase size reduction in the central region **256**. In addition, a higher flame temperature is used to concentrate size reduction in the central region **256**.

The achromatic power splitters **100, 200** are designed so that they will carry light over a fixed range of wavelengths. The most useful range of wavelengths for commercial
15 applications of fiber optics is between about 600 nm and about 1,800 nm.. In one preferred embodiment, the fixed range of wavelengths is between about 1,300 nm and about 1,600 nm, although splitters may be formed with a different fixed range of wavelengths, e.g., between about 800 nm and about 1,000 nm. In various embodiments, the cladding region or the core of one or more of the optical fibers may be doped.

20 The power split ratio is substantially insensitive to changes in the input light and/or environment. Because the way the power is divided depends almost exclusively on the geometry of the core and the cladding, the power split ratio is substantially insensitive to 1)

changes in the polarization of the input light, 2) changes in the temperature of the device, and
3) exposure to ionizing radiation like gamma-ray and X-rays.

Over the range of 1,300 nm to 1,600 nm, variation in power split ratio is less than
about 1%. The sensitivity of the splitters **100, 200** to polarization changes is better than
5 about -30 dB. The splitters **100, 200** are typically operated in the temperature range of about
5° C to about 50° C, although the splitters may be operated at higher and lower temperatures
depending on the application.

In some embodiments, the achromatic power splitter **100, 200** is epoxied to a silica
substrate and/or enclosed in a casing for protection. Figure 8 shows an exemplary
10 embodiment of the achromatic power splitter **100** disposed within a casing **288**, e.g., a metal
cylinder. Typical dimensions for a metal cylinder are about 60 mm in length by about 5 mm
in diameter.

While the invention has been particularly shown and described with reference to
specific illustrative embodiments, it should be understood that various changes in form and
15 detail may be made without departing from the spirit and scope of the invention as defined by
the appended claims.